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Accuracy of inlay and onlay restorations based on 3D printing or milling technique - a pilot study

Keywords

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ABSTRACT

Purpose: To evaluate and compare the accuracy of 3D printing versus CAD/CAM milling in the fabrication of inlay/onlay restorations based on pilot experiments. Material and methods: Different shaped inlay/onlay cavities were prepared on six extracted and root canal treated human molar teeth. Digital impressions were taken with a CEREC AC Omnicam© intraoral scanner. Based on the same impression data, nano-ceramic restorations were performed using milling (M group) and composite restorations (from material not for clinical use) using Multijet 3D printing technology (3D group). The accuracy was evaluated by measuring the marginal and internal gaps based on x-ray microtomography 3D imaging scans. The internal fit was evaluated using a replica technique with A-silicone impressions and weighing. Results: The 3D group restorations showed better marginal and internal fit values. The mean internal gap values of the 3D group restorations were 40-60% lower compared to the M group restorations, the difference being statistically significant at most measuring points ($p<0.05$, t-test). Conclusions: The accuracy of the Multijet 3D printing is at least at the same level as the milling technique in the fabrication of dental inlay/onlay restorations. Additional investigations are needed to develop the 3D printing process and suitable materials for dental applications

INTRODUCTION

In dentistry, restorative materials are needed for repairing damage caused by dental caries as well as for occlusal rehabilitation. Nowadays, composite resins have replaced metal alloy materials and are used as a primary direct filling material worldwide, as they provide better aesthetics and are easier to use.[1] On the other hand, composite resins have higher failure rates and risk of secondary caries compared to amalgam restorations.[2] Due to these shortcomings of the composite properties, and partly due to the demanding techniques, the main reason for their failures are fractures and caries.[3,4] New restoration materials and techniques are therefore needed, especially in the field of restorative dentistry.

The proportion of elderly people and, correspondingly, the number of dentate people is continuously increasing,[5] thus creating a need for the development of long-lasting materials for dental restorations and fixed prosthodontic applications having good aesthetics, durability and effective cost-benefit ratio. One solution for manufacturing these restorations is CAD/CAM (computer-aided design and computer-aided manufacturing) technology that includes both subtractive and additive manufacturing techniques. Dental CAD/CAM systems include digital impression and design software in the CAD phase. In the CAM phase, the designed prosthetic restoration is manufactured.[6]

Additive techniques, also called 3D printing techniques, may provide novel possibilities to overcome the challenges linked with the durability of dental restorations, and may be used to fabricate more complex restorations compared to subtractive techniques at a reasonable cost. In 3D printing, successive layers of material are deposited under computer control to create an object layer by layer. The objects, having practically any shape or geometry, are produced from a model or design in an electronic form. The 3D printable models may be created with a CAD software package.[7] 3D printing technology has already been used in dentistry for printing implant drilling or surgical guides and occlusal splints.[8] Flügge *et al*.[9] demonstrated that digital impressions with the iTero© (Align Technology, San Jose, USA) system can be combined with 3D printing to produce implant drilling guides.

Good marginal and internal fit improve the prognosis of prosthetic restoration. Poor marginal adaptation can lead to gingival inflammation, increased probing depths, and bone resorption.[10] Other biologic complications related to inlay and onlay restorations include recurrent decay, endodontic problems, and tooth fractures.[11] Holmes *et al*.[12] defined marginal gap as the perpendicular measurement from the internal surface of the margin of the restoration to the outermost edge of the finish line of the tooth margin. Most investigators use the criteria of marginal gap established by McLean and von Fraunhofer, who concluded that a maximum of 120 mm is allowed for the marginal gap opening.[13] Values between the range 50 and 200 mm have been reported, with the absence of any objectively accepted threshold.[14] Furthermore, adequate internal fit is important in regard to the durability of restorations, and internal gaps smaller than 122 µm have been reported to increase the fracture strength of ceramic restorations.[15]

3D printing may enable higher restoration accuracy compared to subtractive manufacturing techniques, where accuracy is limited by the milling unit and machining tools. Another benefit is its low material loss.[16] The 3D printing process is fast and in future, likely to be used chairside at the dental office. The aim of the present study was to compare the accuracy of dental restorations prepared using the 3D printing technique to those manufactured with the subtractive technique. The applicability of the digital intraoral impression technique for 3D printing was also evaluated. The hypothesis was that modern 3D printing provides at least as good accuracy as subtractive manufacturing in the manufacture of dental inlay and onlay restorations. Only few studies addressing the possibilities of 3D printing in dental restoration manufacture exist in the current literature.[17-18]

MATERIAL AND METHODS

Six extracted human third molar teeth were randomly collected at the Dental Teaching Clinic of Kuopio University Hospital. Before use, the teeth were disinfected using a chloramine T solution and stored in refrigerated state. The teeth were root canal treated, and all soft tissues were removed. For each tooth, a core-build up was made with Paracore© (Coltene, Altstätten, Switzerland). Inlay/onlay cavities of different shapes and forms were prepared on six teeth according to CEREC© (Sirona Dental system GmBH, Bensheim, Germany) preparation guidelines. Pulpal floors of the cavities were prepared flat, and inner angles were rounded and smoothened with fine diamond burs using water spray cooling. The restorations and their approximate dimensions are presented in Figure 1. Digital impressions were taken of each tooth with the CEREC AC Omnicam© digital impression system. For digital copying, the teeth were inserted into Affinis© (Coltene, Altstätten, Switzerland) putty blocks. The prepared tooth was inserted in the middle of the block and one extracted and unprepared tooth was inserted adjacently on each side of the prepared tooth *(Figure 2*). For each prepared tooth, a separate block was formed, which made up a total of six blocks (n=6). The opposing bite was formed in the same way, except that all three teeth were left unprepared in the block. The same opposite tooth block was used in all impressions. The digital impressions were captured according to the manufacturer's guidelines. During impressions the blocks were held on a flat table. First, the block containing the prepared tooth was scanned. After that, the opposite tooth block was scanned, and finally, the occlusion was formed and captured, inserting the prepared and unprepared tooth block on top of each other in steady state. Based on the hardware display screen, all of the details of the cavities and the surfaces of the adjacent teeth were clearly captured, and no undercuts were detected. The impression process is presented in Figure 3. The digital impression data was transferred from CEREC© 4.4 software to CEREC© inLab SW 15.0 CAD software. The CAD process was carried out in this software using the same digital impression data and marginal design for both manufacturing groups. After the design for the M group restorations, the CAD files were transferred to CEREC© 4.4 software and the data was sent to the milling unit. Restorations were milled using the CEREC MC XL© inLab milling unit from the Lava Ultimate© (3M ESPE, St. Paul, USA) A2-LT/14L blocks. The milling was done according to manufacturer's recommendations. For the 3D group restorations, the CAD data was saved in STL file format in the CEREC© inLab SW 15.0 CAD software. The STL files were not modified before printing. The 3D group restorations were manufactured with a Projet 3500 HDMAX© (3D Systems, Rock Hill, USA) Multijet 3D printer using Visijet M3 Crystal© (3D Systems, Rock Hill, USA) photopolymer material hardened with UV light and 0.016 mm layer thickness (not an approved permanent restoration product). The support material for the printing was Visijet S300© (3D Systems, Rock Hill, USA), the printing orientation was vertical, and the resolution was 750 x 750 x 1600 DPI. The material is Class VI capable for approved medical applications.

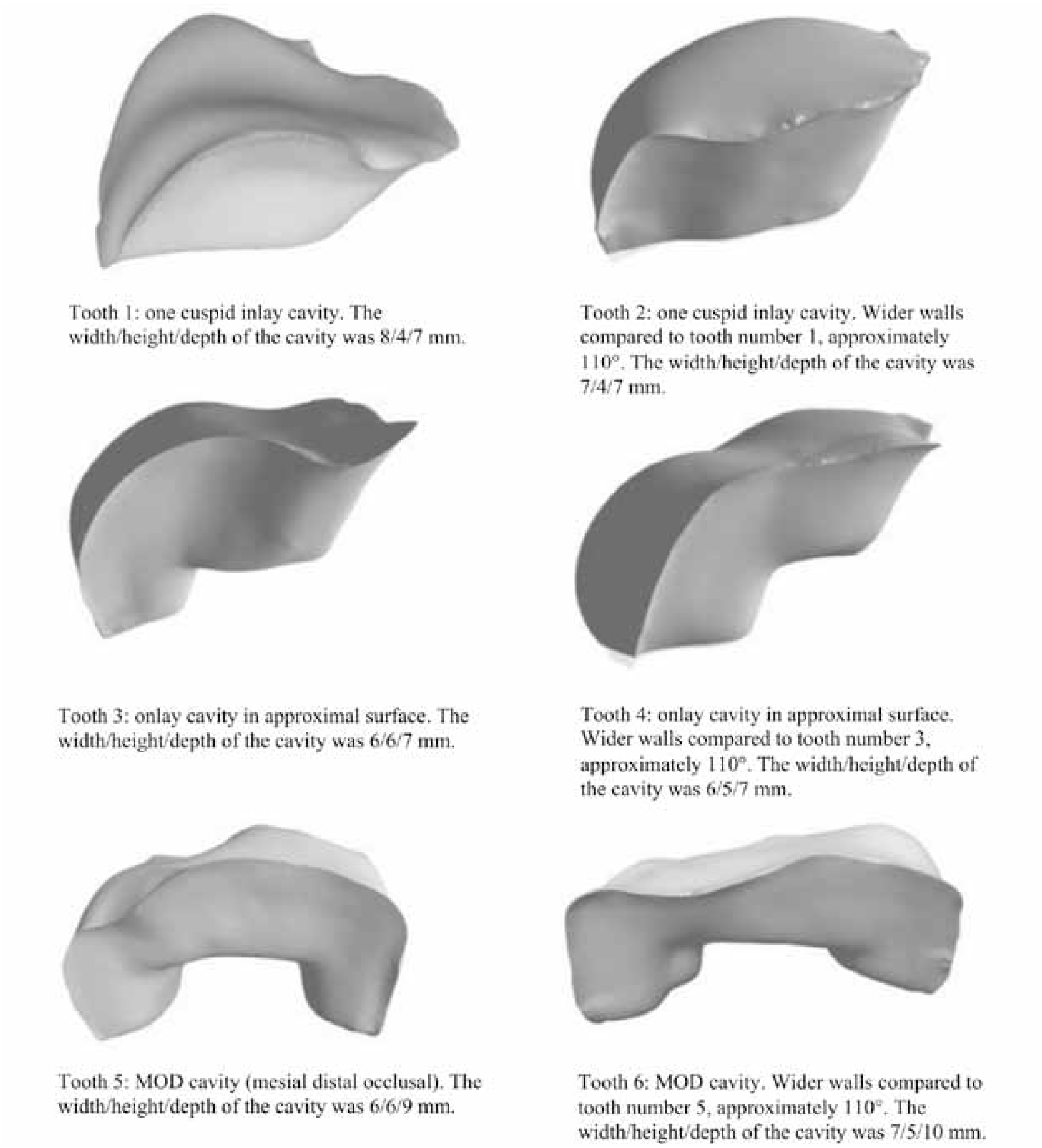

Figure 1: The shape and approximate dimensions of the restorations made with milling and 3D printing.

Figure 2: Representation of the teeth and putty block set-up. For digital copying, the teeth were inserted into putty blocks.

The accuracy of the M and 3D group restorations was evaluated and compared using linear measurements based on x-ray microtomography (micro-CT scans), n=6 per group. The teeth with the restorations were scanned with a desktop SkyScan© (Bruker microCT, Kontich, Belgium) 1172 µCT scanner. Each restoration was fixed in the tooth with an adhesive tape and a light compression cushion. There was just an air layer between the tooth and the restoration, with no cement layer. Scanning was performed at 100 kVp voltage and 100 mA current. An Al+Cu filter was used to remove low energy X-rays. The rotation step was set to 0.40 degrees and a 180 degree rotation scanning procedure was performed. The long axis of the tooth was perpendicular to the imaging X-ray beam. The images had 2000 x 1048 pixels and a resolution of 7 µm.

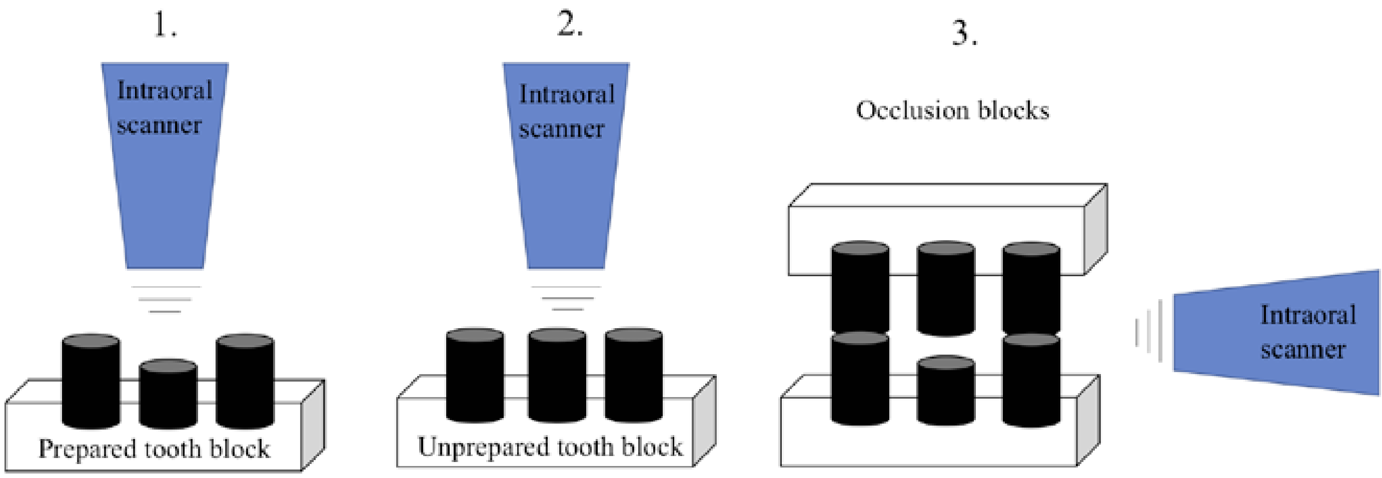

Figure 3: Schematic drawing of the impression process. In Phase 1, the prepared tooth block was scanned, which included one of the six prepared cavities in the middle of the block. In Phase 2, the opposite tooth block was scanned, and in Phase 3, the occlusion was captured. In total, there were 6 different Phase 1 tooth blocks including different shape cavities (n=6), and the described scanning procedure was repeated for each block.

After scanning, for comparison of restorations, the orientation of the images was aligned using alignment marks marked on each tooth in silver paint. Multiple cross-sectional images were obtained using the Data Viewer© software (Bruker microCT, Kontich, Belgium). The correct position of the restorations was confirmed from the micro-CT images by observing at least three contact points between the restoration and the tooth (zero gap). Marginal and internal gaps were measured from mesio-distal sections at the same location in each restoration using the measurement points presented in Figure 4. Each linear measurement was repeated five times.

The average gap between the restorations and the teeth was evaluated using Affinis© light body low viscosity A-silicone. A replica technique was used for the measurements because it has been successfully used in earlier studies.[14,19-20] The cavities were filled with the impression material, and the restorations were pressed onto their corresponding preparation. The impression material used in the measurements had a very low viscosity. Finger pressure was applied on the occlusal surface of the restoration until it came into contact with the tooth. The restorations were held in place with maximum finger pressure for 2 minutes, which is the total working time for the impression material. Upon contact with the surfaces, the silicone was translucently thin and excess material squeezed off. The excess impression material was removed from the outer lines using a surgical knife. Thereafter, the restoration and the impression material were carefully removed. Each gap measurement with the impression material was repeated three times; standard deviations are reported in Figure 5. The standard deviations in the measurements were low, indicating a good reproducibility of the technique. The impression material was weighed with the XSE analytical balance© (Mettler Toledo, Columbus, USA) 0.01 mg precision scale.

STATISTICAL METHODS

The mean values and standard deviations for the marginal and internal fit were calculated based on micro-CT measurements at each measuring point as well as the weight of the impression material. The statistical differences between the M and 3D group micro-CT measurements were analyzed using the Wilcoxon signed rank test. The statistically significant level was set at $p<0.05$. Statistical analyses were performed using IBM SPSS Statistics (version 21.0).

RESULTS

The mean marginal and internal gap values obtained from the micro-CT measurements are presented in Table 1. The 3D group restorations had significantly lower marginal and internal gap values at all measurement points. The average weight values of gap replicas are presented in Figure 5. The internal fit of the 3D group restorations was 40–60% better compared to the M group restorations made using the milling technique.

DISCUSSION

In the present study, the marginal and internal fit of the 3D group inlay and onlay restorations seemed to be better than those of the M group restorations. The M group restorations showed higher threshold values at measuring points 1 and 7 than generally accepted. This is likely to be a result of imprecise fit of the teeth 5 and 6 MOD restorations, which is seen in Table 1 and Figure 5. The result may indicate that these cavity forms are not optimal for the milling technique. Furthermore, each manufacturing phase including tooth preparation, impression capturing and technique, and CAD process can affect the fit of the final restoration. In addition, micro-CT measurements for each restoration were determined from one mesio-distal section, which might not represent the fit in other sections or planes.

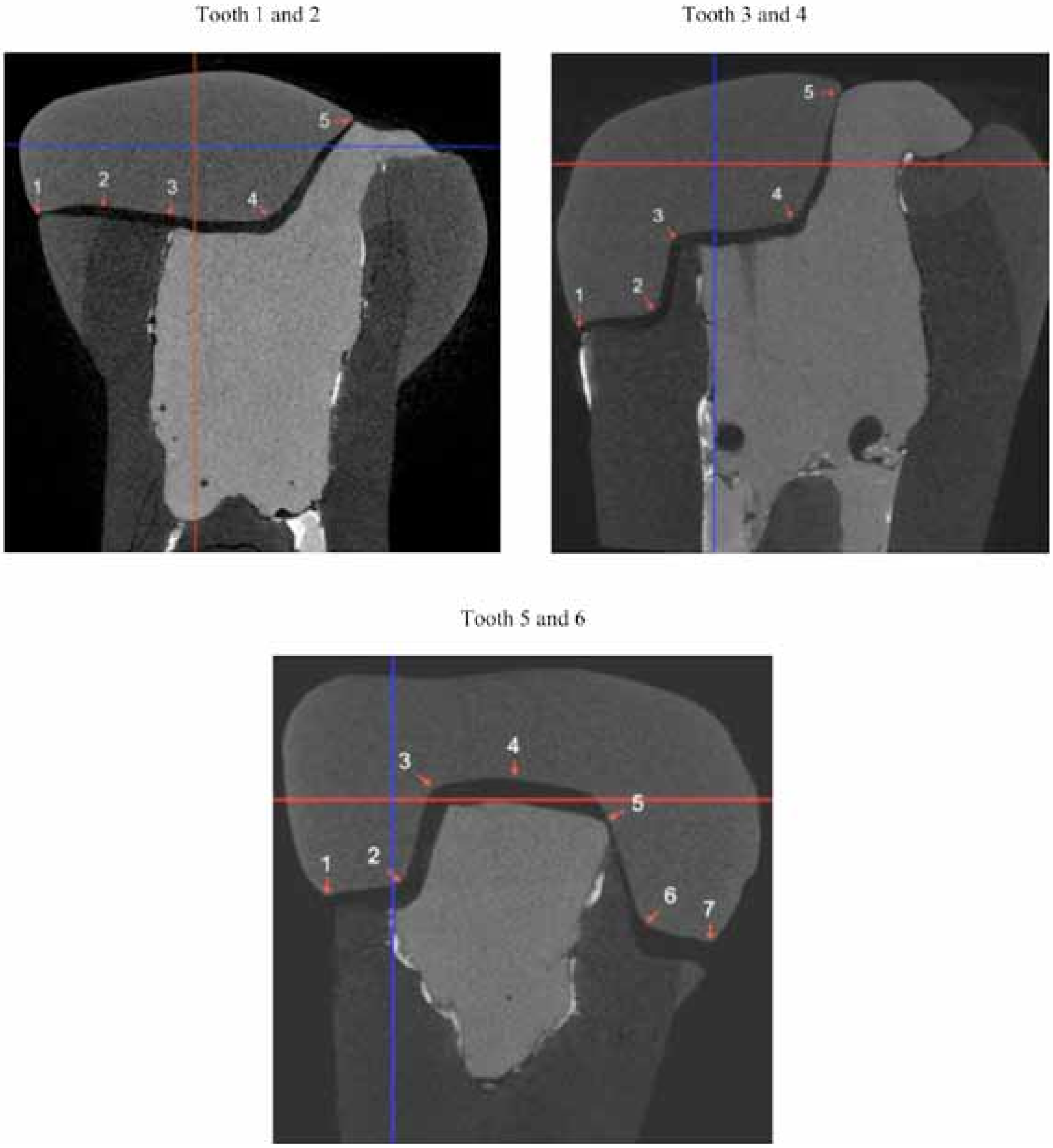

Figure 4: The accuracy of composite resin restorations made with milling and 3D printing was evaluated using linear measurements based on micro-CT scans in mesio-distal sections.

However, exactly the same digital impressions, marginal design, and fit analysis were used for both the M and 3D manufacturing group, and the results indicate that 3D printing may offer a solution for these challenging cavity forms. The accuracy of the 3D group restorations proved to be better compared to the M group restorations at all measuring points and different shapes and form of cavities. This may indicate that 3D printed restorations are not so sensitive to cavity preparation guidelines, and more accurate complex shape restorations can be manufactured using the additive manufacturing technique compared to the subtractive milling technique. More studies with larger numbers of different kind of teeth and cavities are needed to confirm the findings before drawing definite conclusions. There are some uncertainties related to the techniques which should be noted when comparing the results between the studies. These include, for example, differing stiffness of the restoration materials, viscosity of the impression material at the time of placement, and the pressure applied. However, exactly the same procedures were used here for both study groups, and both techniques provided data with good reproducibility and consistence. In addition, the Visijet M3 Crystal© photopolymer material used in the present study was not approved for permanent restorations, but it was chosen because it provides high detail accuracy for the Multijet 3D printing. In the present study, the object was to optimize the manufacturing accuracy of dental inlay and onlay restorations using the additive manufacturing technique, but the biocompatibility of the 3D printed restoration materials still needs development and further studies. The printing accuracy depends on the materials and parameters used. Most earlier studies have focused on resin printing. For example, printing orientation and resin color affect the printing accuracy, which is partly due to laser light intensity, and samples printed at 90° orientation using white resin color had proven to be the optimal combination.[21] The effect of manufacturing parameters on the dimensional accuracy of 3D printed crowns manufactured using stereolithography 3D printing technique was evaluated in another study. The researchers concluded that a build angle of 120° combined with a thin support type provided the highest dimensional accuracy values.[22]

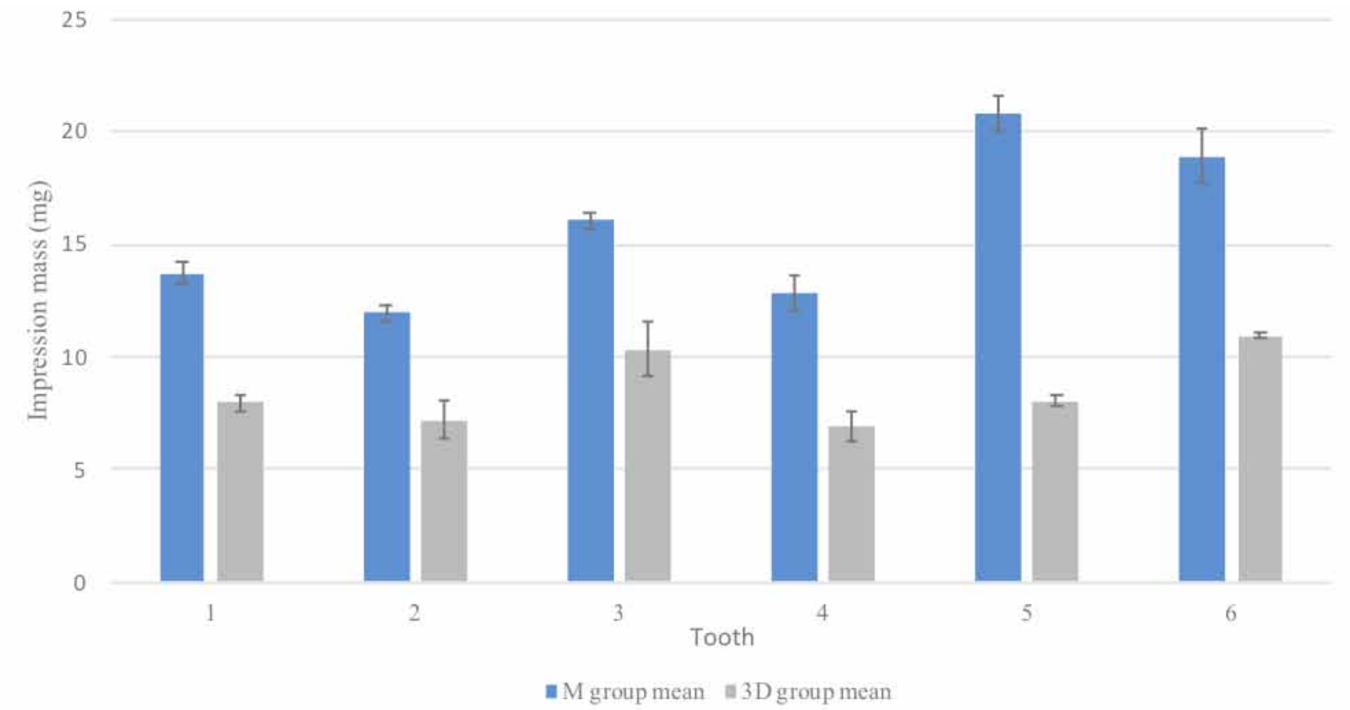

Figure 5: Comparison of replica weights and standard deviations between the restorations and abutment tooth. In each case, there were three parallel independent measurements, n=3 (mg, M group=milled restorations, 3D group=3D printed restorations).

Table 1. Mean values of marginal and internal gap measurements in the mesio-distal sections at different measuring points (Fig. 3), based on micro-CT scans (µm).

Measuring point*	Number of teeth	M group (µm)	3D group (µm)	p value
1	6	166±67	68±23	0.028**
2	6	297±73	95±60	0.028**
3	6	277±74	80±45	0.028**
4	6	310±78	102±51	0.028**
5	6	86±27	54±22	0.046**
6	2	362±137	77±74	0.180
7	2	509±126	182±222	0.180

* Each linear measurement was repeated five times.
**Indicates statistically significant difference, p<0.05.

A study by Molinero-Mourelle *et al.*[23] reported clinically acceptable marginal fit values for provisional crowns manufactured using fused deposit modeling 3D printing technique and Polylactic acid material, which is a thermoplastic biopolymer commonly used in FDM printers. In conclusion, high printing accuracy can be achieved when the CAD model is sliced in very thinly slices and the printed layer thickness is minimized. In turn, thicker layers can be used for cost-effective production and to accelerate the manufacturing process, but this results in poor surface finish and visible staircasing.[24] Only few studies exist in the literature regarding the possibilities of 3D printing in the manufacture of dental restorations. Eftekhar Ashtiani *et al.*[17] reported that the onlay restorations manufactured by conventional impression and conventional fabrication proved to be more accurate than 3D printed onlay restorations, although the fit was clinically acceptable in both manufacturing groups. In their study, the Micro plus Hi-Res© (Envision TEC, Detroit, Michican, USA) 3D printer was used, which probably influenced the results because the technique and equipment have a significant impact on the printing accuracy. In contrast, the results of the present study seem to be promising, as has also been seen in previous studies. A study by Revilla-León *et al.*[25] reported clinically acceptable marginal and internal gaps (<100 µm) for handmade, milled, and 3D printed wax patterns for lithium disilicate onlay restorations, although the best fit was found for the handmade group. Dental copings manufactured using direct metal laser sintering 3D printing technique showed superior marginal and internal accuracy compared to subtractive techniques. In addition to a better fit, the additive manufacturing technique provides cost-effectiveness in production and can increase the longevity of teeth and prostheses thanks to improved fit.[26] Other benefits related to additive manufacturing techniques include the speed of the manufacturing processes, although the cost of the technique remains its main shortcoming.[27]

Very few studies exist in the literature concerning 3D printing accuracy in other dental applications than restoration manufacturing. For example, in orthodontics, dental models are used for treatment planning. The mechanical properties and dimensions of 3D printed orthodontic models have proven to be clinically acceptable.[28] Lee *et al.*[29] investigated the accuracy of 3D printing for manufacturing replica teeth. In their study, digital impressions were taken from fifty extracted molar teeth, and replica teeth were manufactured using FDM (fused deposition modeling) and PolyJet technology. Based on the measurements, replica teeth manufactured using FDM tended to be slightly smaller, whereas replicas manufactured by PolyJet tended to be slightly larger than the extracted teeth. An *in vitro* study by Mai *et al.*[18] evaluated the fit of interim crowns fabricated using photopolymer-jetting 3D printing. They reported that 3D printed crowns were more accurate in the occlusal region compared to milled crowns and ones manufactured with compression moulding methods. Chen *et al.*[30] conducted an *in vitro* study of patient-specific implant dentistry and 3D printed customized implants. They showed that the laser melting 3D printing technique is an efficient way of printing fully dense customized implants with high strength and adequate dimensional accuracy. A case report by Revilla León *et al.*[31] described successful use of selective laser melting and electron beam melting 3D printing techniques in the fabrication of metal frameworks of the implant-supported fixed dental prostheses (FDPs) for the rehabilitation of occlusion in edentulous patient.

In dentistry, CAD/CAM technology has been used since the 1980s.[32] The fit of inlay and onlay restorations fabricated using dental CAD/CAM systems are widely reported to be clinically acceptable. Guess *et al.*[33] evaluated the marginal and internal fit of heat-pressed versus CAD/CAM fabricated ceramic onlays in 72 teeth. Restorations manufactured with CEREC© inLab 3D Software V3.01 had marginal gaps less than 100 mm. Keshvad *et al.*[34] conducted an *in vitro* study to evaluate the marginal gap of leucite-reinforced ceramic inlays fabricated with the CEREC© inLab system and the hot-pressed technique. In their study, all reported marginal gaps were clinically acceptable and less than 100 mm. The accuracy of digital impression techniques for fabrication of crowns and short FDPs has proven to be clinically acceptable.[35] Based on mainly *in vitro* studies,[36] the digital impression technique is sometimes reported to be even more accurate than conventional impressions for fixed prosthodontics fabrication. Wesemann *et al.*[37] studied the accuracy and efficiency of full-arch digitalization and 3D printing. They concluded that for prosthodontic use, the scanning scope should be less than one quadrant and three teeth. Based on those findings, the accuracy of digital impressions should be appropriate to be used for dental inlay and onlay restoration manufacture with the 3D printing technique.

In this study, the studied teeth were precisely prepared by an experienced clinician according to the preparation guidelines of the CEREC© CAD/CAM system. There were no undercuts or tight corners, and minimum material thickness was ensured. The digital impression was carefully captured: all details of the cavities and all surfaces of the adjacent teeth were accurately copied. Although the same digital impressions and marginal design were used for both milled and 3D printed restorations, the accuracy of the final restoration might decrease in the manufacturing process. The accuracy of the milled restorations might decrease due to data transfer from the CEREC© 4.4 software to the CEREC© inLab SW 15.0 CAD software because in chairside use, these operations are not needed, and the data might be affected during export. Similarly, the file format transfer to the STL format might influence the accuracy of the 3D group restorations. In the present study, a µCT device was selected for marginal and internal fit measurements because it provides high resolution data at the micrometer scale,[15] and a resolution of about 7µm was chosen, allowing quantitative comparisons of fit in different locations. This technique is generally recommended and has been used by other investigators for marginal and internal gap measurements.[38-42] In addition, image analysis might influence the final results. Micro-CT section images are inaccurate if two materials have similar density. Therefore, it is difficult to determine the exact point of interface of the restoration and the tooth.[42] The Replica technique was used for average gap measurements besides micro-CT measurements because a combination of two measurement methods is recommended for FDPs' marginal adaptation measurements.[43] The replica technique gives the average fit but not the local variation, which is an additional reason why micro-CT imaging was used: to enable measurement at distinct points. The mean internal gap could also be calculated by converting the DICOM data from micro-CT to the 3D reconstruction image, and afterwards, by segmenting the gap space and calculating the space using specialized software, but the replica technique was chosen due to its proven track record of successful and reliable use in earlier studies.[14, 19-20] On the other hand, using maximum finger pressure for replica measurements is not the optimal methodology used for internal gap measurements as the results could depend on the non-constant pressure force. This should be considered when the results are compared. The number of the studied restorations was relatively low because the present study was a preliminary study to evaluate the accuracy of the Multijet 3D printing used in fabrication of inlay/onlay restorations; consequently, no strong conclusions can be drawn. Despite this, the marginal and internal fit of the 3D printed inlay and onlay restorations proved to be at least at the same level as that of restorations manufactured using the milling technique. This indicates that compared to milling, more complex restorations can be manufactured. In addition, the 3D printing technique does not have the same constraints as the subtractive milling technique. The accuracy of the printed restorations is not limited to the milling unit's machining tools, and the material options used in this technique are wider. Furthermore, any systemic differences between the model and the printed restoration can be easily corrected during printing. In turn, compared to milling systems which have shown their potential in clinical use over a few decades, there are currently no commercially available 3D printing materials or manufacturing systems approved for permanent dental restorations manufacturing, which must be taken into account when assessing the possibilities of additive manufacturing in the field of restorative dentistry. Further studies are needed to develop the dental 3D printing process and, especially, the materials for permanent restorations.

CONCLUSIONS

Within the limitation of the present study, the following conclusions can be withdrawn:

1. The accuracy of Multijet 3D printing is at least at the same level as that of milling technique in the fabrication of dental inlay and onlay restorations. Due to the relatively low number of studied restorations, the results can be regarded as preliminary, and additional investigations are needed to confirm these findings using a larger set of specimens.
2. Additional studies are needed to improve the 3D printing process for dental applications, especially with regard to finding suitable materials for biocompatible and long-lasting restorations.

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DISCLOSURE STATEMENT

The authors report no conflict of interest.

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MANUFACTURER'S DETAILS

- iTero©, Align Technology, San Jose, USA.
- Paracore©, Coltene, Altstätten, Switzerland.
- CEREC©, Sirona Dental system GmbH, Bensheim, Germany.
- Affinis©, Coltene, Altstätten, Switzerland.
- Lava Ultimate©, 3M ESPE, St. Paul, USA.
- Projet 3500 HDMAX©, 3D Systems, Rock Hill, USA
- Visijet M3 Crystal©, 3D Systems, Rock Hill, USA
- SkyScan©, Bruker microCT, Kontich, Belgium.
- Data Viewer©, Bruker microCT, Kontich, Belgium.
- XSE analytical balance©, Mettler Toledo, Columbus, USA.
- Micro Plus Hi-Res©, Envision TEC, Detroit, Michigan, USA.

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